An AI-Based Diagnostic System for the Abrams Tank

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Abstract

The U.S. Army holds title to one of the most envied weapon systems developed-the Abrams main battle tank (MBT). Militarily, this weapon represents the epitome of lethality and survivability on today's modern battlefield. To combat difficulties associated with maintaining this sophisticated weapon, the U.S. Army Research Laboratory (ARL) and the U.S. Army Ordnance Center and School (OC&S) combined technologies from artificial intelligence with Army tank maintenance doctrine to develop an expert diagnostic system to assist Abrams' mechanics. The system, known as Turbine Engine

Diagnostics (TED), targets the mechanic's ability to effectively and efficiently diagnose and repair the Abram's engine and transmission. The OC&S estimates that TED will save over $8 million annually by enhancing the Abrams mechanic's troubleshooting capabilities. Limited fielding of TED began in July 1994 to 60 National Guard units in 30 states. Active units of the U.S. Army will receive TED in FY96. This paper examines the relevant background, development issues, system overview, test results, and future efforts surrounding the TED project.

1. INTRODUCTION

The Gulf War confirmed the attestation by the U.S. Army armor community that the Abrams main battle tank (MBT) epitomizes lethality and survivability on today's battlefield. Logistically, on the other hand, the negative corollary is that the Abrams MBT is expensive to operate, support, and maintain. Central to these costs is the maintenance for its engine and transmission.

Maintenance on the Abrams MBT is accomplished at as many as four levels: organization, direct support (DS), general support (GS), and depot. Items that cannot be fixed at one level are sent to the next higher level. The lack of GS facilities complicates engine and transmission maintenance. Engines that cannot be fixed at DS are sent to depot, and depot is usually in the United States. See Figure 1.

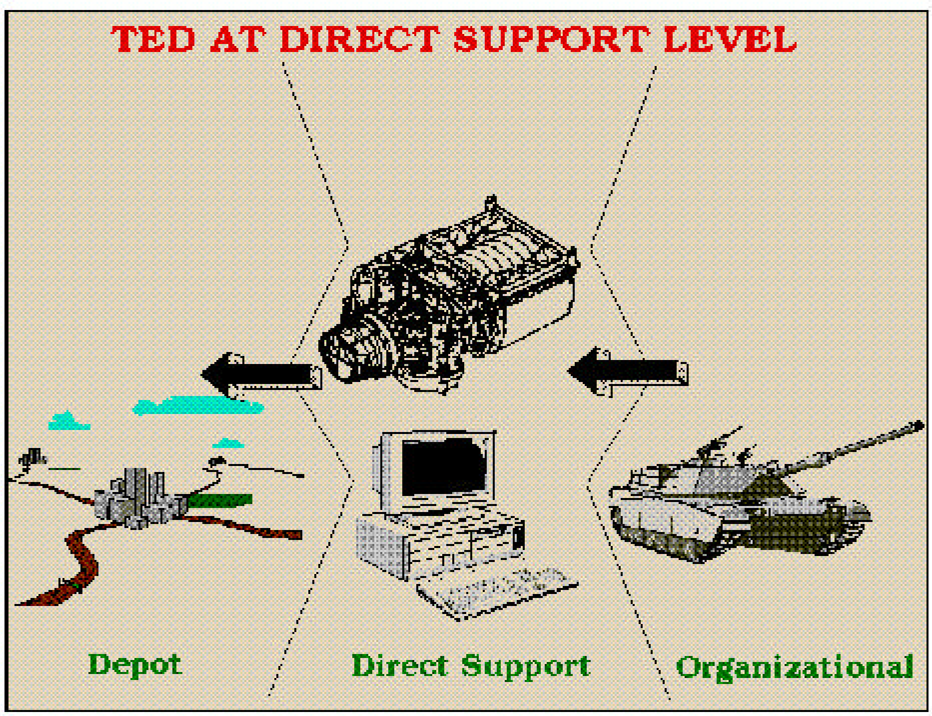

Figure 1: Maintenance-Level Military Structure

While many Army organizations are responsible for ensuring operational readiness of the Abrams fleet, it is the DS mechanic that is central to ensuring the Army's maintenance philosophy to Fix Forward. The Government's shrinking budgets, continued downsizing, and skill consolidation complicate this effort. Recognizing these facts, the U.S. Army Research Laboratory (ARL) and the U.S. Army Ordnance Center and School (OC&S) have focused research efforts to provide the DS mechanic with new maintenance capabilities. The result of the combined effort is the development of a diagnostic expert system, known as Turbine Engine Diagnostics (TED).

The TED program started in 1991 at the OC&S as an effort to solve some of the maintenance problems the Army was having with its equipment. ARL joined the program in the summer of 1991 as knowledge engineers and technical advisors, with the OC&S supplying the subject matter experts (SMEs) to provide the expert diagnostic knowledge and to guide the development direction of the system. The OC&S also supplied engines and soldiers as needed to test the new software being developed.

The first TED prototype was ready by January 1992. For the next 18 months, existing modules were expanded and new modules were begun. In March 1993, the TED program was nominated and received the American Defense Preparedness Association's award for outstanding logistics and artificial intelligence (AI) application. By August of the same year, the program was sufficiently developed to warrant formal field testing. Preliminary results showed TED improved faults identification by 96% over the older manual methods.

In January 1994, Program Manager-Abrams (PM-Abrams), the primary proponent for the Abrams tank, decided to field TED to all active DS units with Abrams tanks in FY96. In addition, further production of paper manuals for the AGT1500 engine was halted. By March of the same year, the National Guard Bureau (NGB) asked to have TED for its National Guard units as soon as possible. Fielding to the first two National Guard units (Georgia and Tennessee) began in July 1994. The National Guard Bureau continued to incrementally field TED until 60 units in 30 states with Abrams tanks had the TED software.

2.0 Developmental Issues

The development of any large-scale computer system requires extensive amounts of time and resources; expert systems are no exception. Careful consideration must be given to a myriad of issues. The following section outlines the critical issues that were part of TED development process.

2.1 Motivation (Domain and Scope Selection)

The principal reasons for developing an expert system are to disseminate rare or costly expertise and to more effectively and efficiently use the human expert (Weiss and Kulikowski 1984). The selection of an appropriate domain with proper scope is critical to its success. The domain selected should be one that encompasses a problem that is "worthy" of the effort. The specificity within the domain defines the scope of the project. For the TED program, Abrams tank maintenance was quickly identified as the proper domain with special focus on the engine and transmission.

By 1991, several factors were contributing to the selection of tank maintenance as an appropriate domain. First, the cost to maintain the Abrams MBT engine represented the largest portion of its operation and support costs. One study determined that, in one year, 39% of the 360 engines evacuated to depot were reported as no evidence of failure (NEOF). This means 39% of the engines returned to depot were actually in running condition and should not have been sent to depot. The unnecessary cost related to NEOF conditions was $18.2 million (Textron, 1988).

A second reason for choosing tank maintenance dealt with a new funding directive called Stock Funding of Depot Level Repairables (SFDLR). If you were a company commander in the past, and one of your tanks broke down, it was fixed for free (as far as you, the commander, were concerned). Today, as that same commander, you are billed for your maintenance costs. The hope of the new doctrine is that it will reduce overall maintenance costs, without adversely affecting unit readiness. Fortunately, the Army realized that SFDLR alone, without better maintenance aids for the mechanic, was not the final answer to reducing high maintenance costs.

The third reason for choosing a tank maintenance domain was a new Army maintenance doctrine. Under the new doctrine, when an engine fails, it is pulled from the tank and sent to DS. The tank hull remains at the unit, a new engine is sent forward, and the tank is quickly returned to full operational status. This new maintenance concept is called Fix Forward. Under the new DS concept, the mechanic can now perform repairs previously not authorized. Along with the new authorized tasks come new tools previously available only at higher maintenance levels and new lists of spare parts that can be ordered. New maintenance procedures and new methods were necessary to accompany this change.

2.2 Hardware Constraints

An invariable factor associated with every software system developed is hardware constraints. From the onset, careful consideration must be given to the delivery platform (i.e., on what machine or machines will the system reside). Where possible, the identification should occur immediately. The earlier a target machine is identified, the sooner the program can capitalize on its strengths and minimize its weaknesses. For many applications, selection of the delivery platform is a moot point. Where selection is possible, dialog with the user is paramount, giving special consideration to cost, the user's environment, available software, and connectivity.

For the TED program, hardware constraints were predetermined. The delivery platform selected was part of the Army common hardware called the contact test set (CTS) III. CTS III is a DX-33 MHZ or DX-50 MHZ 80486 processor that employs 8 megabytes (MB) of RAM and either a 200- or 500-MB hard disk drive. It is capable of running either the SCO Unix Operating System or Microsoft DOS 6.2 with Windows 3.1. The goal is to field a CTS III to every team of mechanics.

2.3 Software Selection

In the past, computer systems were typically characterized by the proprietary coupling of unique software to a specific hardware platform. Today, contemporary computer systems are breaking the sole-source syndrome and emphasizing greater interoperability and portability. The number of systems adopting the "collection-of- components" approach is increasing; better known as commercial off-the-shelf (COTS).

In general terms, COTS software supports a large commercial following, is readily available, and easily meets or extend a system's capability requirements. Systems developed using a COTS approach are generally less costly, quicker to be fielded, and more flexible than products developed with non-COTS methods. Limiting the COTS approach are the careful examination that is required to correctly match system requirements with the COTS model, the potential for run-time fees, and the need for specialized wrapper programs. While the true efficacy of COTS products is not without bounds, the benefits outweigh the costs.

For the TED program, the adoption of COTS software was considered beneficial. Time was judged better spent on knowledge acquisition and testing than on pure code development. The commercially available procedural-based expert system shell, Visual Expert, by Softsell, was chosen as the primary subsystem. COTS products from Visual Basic, Access, Toolbook, and HyperWriter provide additional features to the TED program. The in-house code was developed using Microsoft C++ and Borland's Delphi.

2.4 Project Management

Dramatic changes are occurring in the way project managers are looking to manage software projects. The traditional life-cycle model, also known as the waterfall method, emphasizes a systematic approach of dividing development into exact stages. Current strategies promote the rationale for rapid prototyping and an incremental development.

Boehm's spiral model (Boehm 1986) incorporates an incremental development schema. Successive prototypes are produced that expand user requirements. In addition, the programmer is able to break complex tasks into smaller components. As each component is developed, it is evaluated against user requirements. The user requirements are reevaluated as each successive module is developed. Consequently, the user is an integral part of the development team.

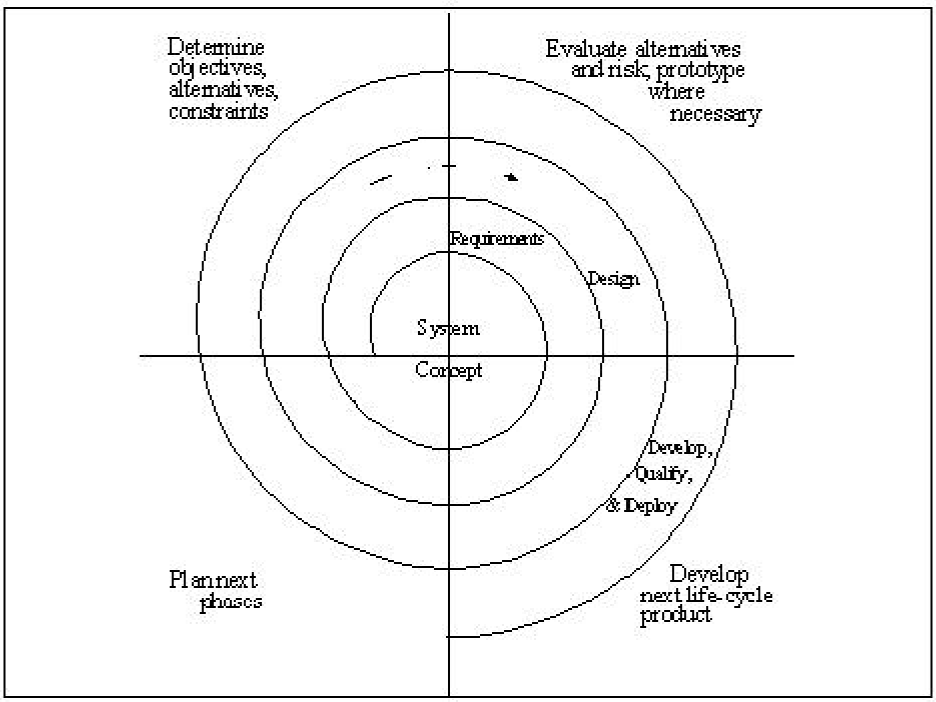

Figure 2: Spiral Model

The TED team adopted the spiral method for this program for many reasons. One was the fast-paced changes occurring in personal computer (PC) hardware and software. It was an easy guess in 1991 that hardware and software for the PC would continue to improve and become more affordable. Computer memory continues to expand and deflate in price. Hard drives continue to get bigger and cheaper. Screen resolution expands and video cards improve. The price of a Pentium system today rivals the price of a 386 system in 1991. Software has followed a similar pattern. Every year, software improves, new products are announced, and existing products offer upgrades at an astounding pace and more reasonable prices.

A second reason to use this iterative approach was that the user, at the start of a project, can rarely envision how technology can improve his or her job. A system based on initial user expectations will at best be shallow and may even be useless. The TED team adopted a soldier-centric paradigm that emphasized support rather than supplant as the end product. This method of open communication better enabled the team to leverage the experience of the SMEs while ensuring continuous soldier feedback during the incremental development. As a result, early prototypes gained quick acceptance and greatly added to the momentum of the program.

In the early years of the project, the software was tested weekly using students in the OC&S. After the first formal test in August 1993, the need for testing was relaxed and is now done once a month using students from the OC&S. Additional user feedback is also provided monthly from the National Guard units that have received TED. Feedback from users may lead to small easy changes to the system, or it may lead to new system features or to new software modules.

3.0 System Overview

The following section provides a general overview of the TED system. The design goals, reasoning technique, and system layout are outlined.

3.1 Design Goals

Early into the project, the SMEs and ARL representatives established several design goals. These goals were based primarily on the SMEs' extensive experience as mechanics and instructors for engine maintenance classes. The SMEs had extensive experience with soldier mechanics—their likes and their dislikes. The following are the main design goals for the TED software. The software should be:

- accurate,
- easy to use,
- flexible,
- task oriented, and
- it should support multiple levels of expertise.

First, the software should be accurate. It need not be perfect, but it should be significantly better at diagnosing faults than the system it is replacing. Otherwise, it will lose soldier respect and it will not be used. Second, it must be easy to use, or otherwise, it will sit on the shelf. Mechanics have favorite stories of diagnostic equipment that does nothing but occupy lots of storage space. Third, it must be flexible enough to support a variety of diagnostic styles. For example, some mechanics are thorough and methodical, and a structured step-by-step approach is best for them. A few have a sixth sense and "know" what is wrong with an engine. They have only limited need for the information in TED and will only use it as an occasional reference. Other soldiers are a mixture of styles. They may know a lot about some parts of the engine but need guidance in other areas.

The fourth goal is that TED be task structured in a way that is natural for the soldier. The current technical manuals (TMs) have a structure that is difficult to use and to follow. Experts can navigate the TMs, but others find the structure confusing. The last goal recognizes that mechanics come with different skill levels. Experts need little or no help from TED. Beginners need extensive step-by-step instructions. A system aimed at just one level of expertise would bore the expert and baffle the beginner.

3.2 Reasoning in TED

The main diagnostic software in TED is a Windows-based shell called Visual Expert from SoftSell. Visual Expert is based on a reasoning paradigm called Procedural Reasoning System (PRS) (Georgeff and Lansky 1983, 1986). PRS is a visual method of encoding reasoning strategies used by expert problem solvers. The knowledge is represented graphically with semantics suited to the procedural, goal-oriented style of problem solving, and PRS is best suited for problems that are both procedural and goal oriented. A procedural approach uses an ordered step-by-step prescription to obtain a desired result, possibly including alternate paths in case of failure. Such an approach is also goal oriented if some steps are goals to be achieved rather than specific actions to be performed (Advance Decision Systems 1988). Army TMs closely follow this paradigm. They are often graphical in nature with decision trees displayed on the page. Some nodes represent goals to be achieved; others represent specific tasks to be performed. These tasks can themselves become goals whose solution is to be given on another page (or in another manual).

PRS combines features from several programming paradigms. Like PROLOG, it has goal-directed inferencing and depth first search. Like expert system shells, it provides a frame system for global objects. Like LISP, it is well suited for rapid prototyping. SMEs quickly learned how to read Visual Expert's visual code, and some began writing their own code or modifying code written by the knowledge engineers.

3.3 System Organization

On its highest level, TED can be viewed as an amalgamation of several expert modules that use a relational database as the common control structure. To facilitate access to the information, TED uses a menu-driven interface. The following section outlines this interface and its underlying information.

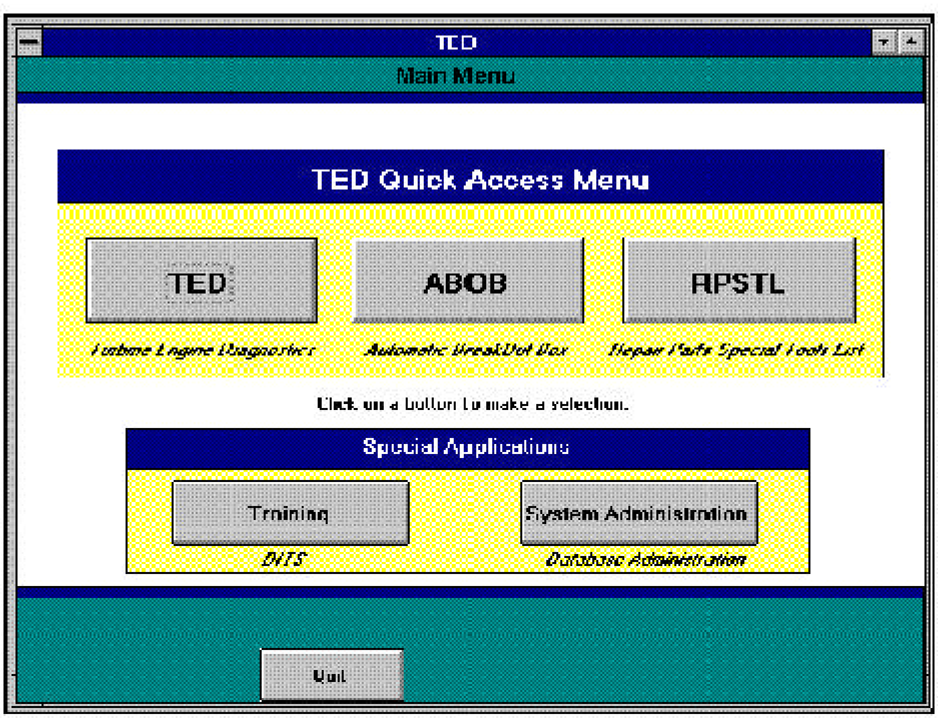

Figure 3: TED Main Menu

From TED's main menu, the mechanic is given access to the entire TED system. As seen in Figure 3, TED separates this access into three main modules and two special applications. The first main module, entitled TED, directs the mechanic to the bulk of the diagnostic and maintenance expertise. The second main module, automated breakout box (ABOB), allows the automatic interrogation of the signals from the engine. In the final main module, repair parts and special tools list (RPSTL), is found the automation of the repair parts and special tools system. Under the two special applications are the diagnostic intelligent tutoring system (DITS) and special system administration functions.

3.3.1 TED Module

The main TED module separates the troubleshooting and maintenance routines into the three specific areas: Inspections, Operational Checks, and Maintenance (see Figure 4).

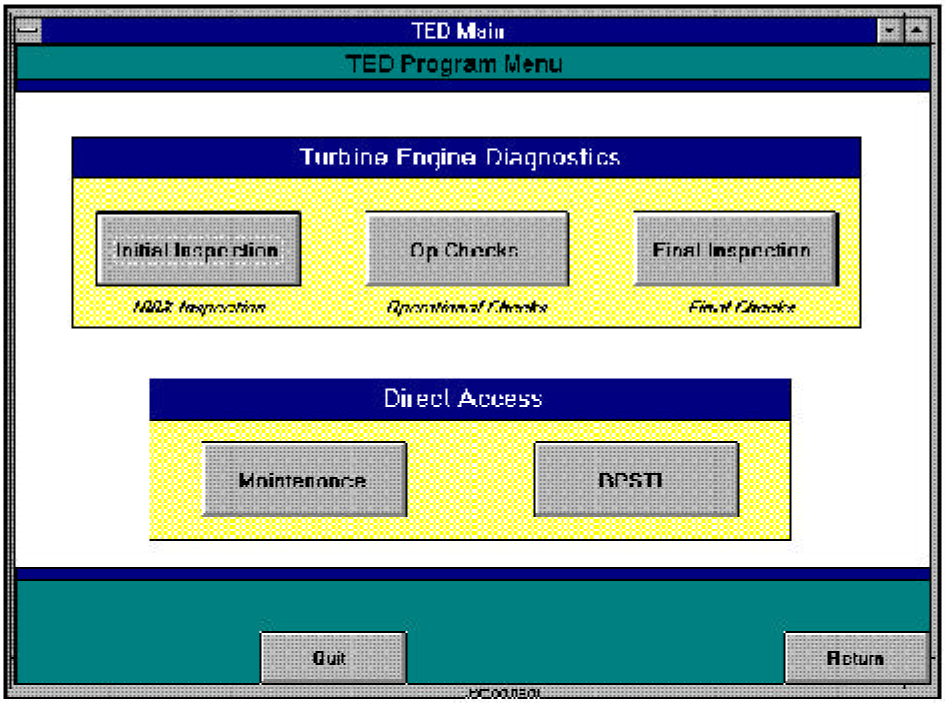

Figure 4: Diagnostic and Maintenance Routines

- Inspections. The inspections modules guide mechanics through a series of detailed inspections of the engine. The engine is divided into separate inspection stations, and at each station, the routines guide the mechanics through a 100% inspection of that region. Upon completion, an electronic DA Form 2404 with noted deficiencies is automatically generated. When deficiencies are noted, TED automatically links to pertinent sections of maintenance and repair parts modules.

- Operational Checks. The second area under the TED module are the operational checks. The operational checks organize DS diagnostic logic by terms easily recognized by mechanics, regardless of experience. Troubleshooting areas include: No Start, Low Power, High Oil Consumption, Engine Smokes, Metal Contamination, Quick Coast Down, Idle Faults, Engine Shutdown, and Protective Modes. Each of the nine submodules contains diagnostic logic to first determine the cause of the faulty symptom, and once the cause has been detected to link the appropriate maintenance and repair parts modules.

- Maintenance Procedures. Maintenance actions for any component include adjust, repair, remove, and replace. The procedures can be invoked in either browse mode or data-driven mode. When in browse mode, maintenance procedures are manually selected through menus and submenus. This provides experienced mechanics the flexibility of viewing only the procedures that they need, while bypassing familiar or routine tasks. When in the data- driven mode, TED automatically establishes the correct links to all pertinent maintenance procedures and to sections of the repair parts manual.

3.3.2 ABOB Module

The ABOB main module provides the mechanic an interface to the ABOB. Developed by Dr. Mark Kregel from ARL, the ABOB is an automated version of the breakout box (BOB), which is a diagnostic tool that is currently in the field. Mechanics employ the BOB, connected to the vehicle's electronic control unit, as an alternate troubleshooting method to determine the operational status of the engine.

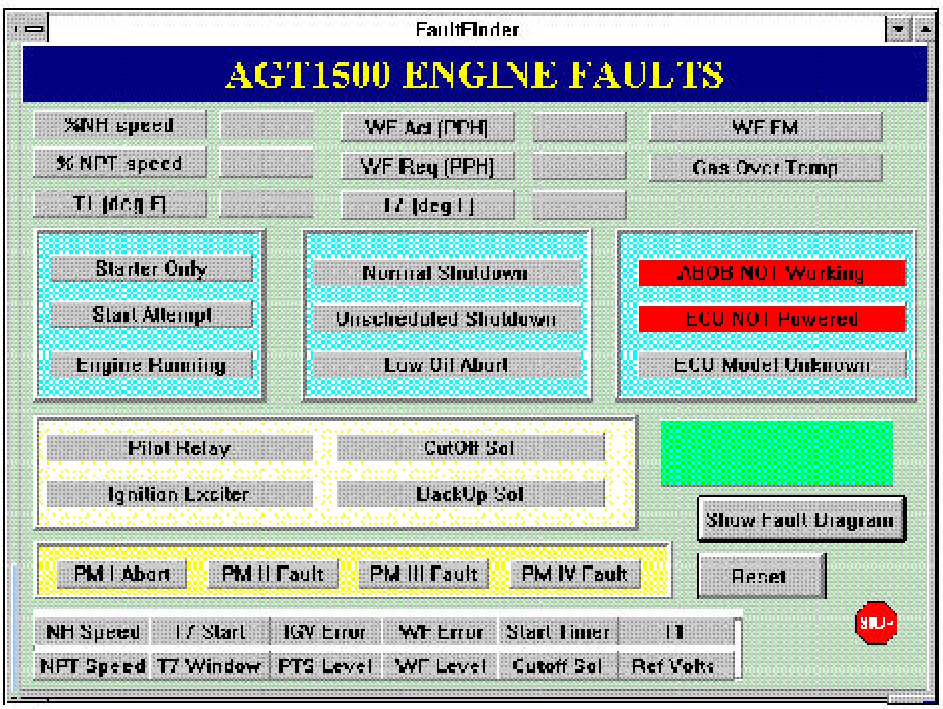

Figure 5: ABOB Interface

ABOB contains an electronic circuit capable of reading 128 channels in a fraction of a second. These signals are passed to the CTS through a standard serial port. ABOB can be used with or without TED to display voltages on the CTS screen in either numerical or graphical format. The ABOB software automates the manual tasks associated with the BOB by providing instantaneous access to all of the engine's voltage signals. When TED is run with ABOB, signals can be automatically monitored, and when a fault occurs, mechanics will be notified of the problem. Figure 5 shows one of the ABOB interface screens available to the mechanic.

3.3.3 RPSTL Module

The third main module of TED is the RSPTL module. This module greatly enhances the mechanics ability to interrogate the parts ordering information for every aspect of the Abrams engine and transmission. The mechanic is provided the ability to search for items of interest in a variety of ways. In addition to being automatically linked from a diagnostic procedure, the mechanic can peruse the system from a general table of contents or choose to search for a specific part number, national stock number, or nomenclature.

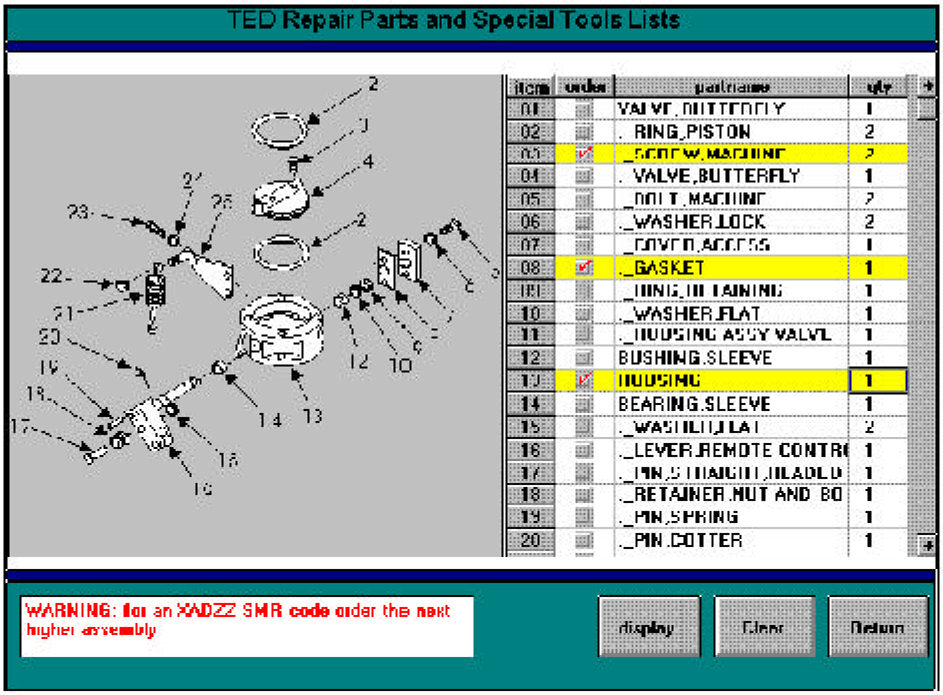

Figure 6: Typical Parts Ordering Screen

Displayed in figure 6 is a typical ordering selection form. For each figure, its associated parts list is displayed on the right side, while its drawing is detailed on the left. Items are selected from the parts list by buttoning the particular order box. When necessary, portions of a drawing may be magnified to highlight areas of interest. Information from the RPSTL is automatically associated with its corresponding work order.

3.3.4 DITS

The first of the special applications is DITS. DITS is an embedded tutorial system that covers basic maintenance procedures, theory of engine operations, and guidance on such tasks as hooking up the Ground-Hop Support Set and using a multimeter. Using interactive review and troubleshooting modules, mechanics can hone their skills in a field environment. DITS, a diagnostic trainer, complements TED, a diagnostic tool, by providing mechanics a complete system.

3.3.5 System Administration

The report writing and database maintenance functions are found under the System Administration module. In addition to allowing the mechanic the ability to print the necessary DA Form 2404 Technical

Inspection Form, the system provides numerous work order and statistical summaries. For the database maintenance, routines to update and delete information are also available.

4.0 Test Results

During the week of 15 - 21 August 1993, an initial field test of the TED program was conducted at Fort Stewart, GA. Participating in the test were 30 soldiers from the Support Squadron, 278th Armored Cavalry Regiment and 771st Maintenance Company, 176th Maintenance Battalion of the Tennessee Army National Guard (TNARNG). Keeping in mind the target audience (DS mechanics), the test had two objectives: First, measure how accurately and quickly mechanics could identify randomly assigned faults on the engine using TED versus using TMs; second, decide if the program was soldier-friendly. For the test, the 30 mechanics were divided into 3 levels of 10 mechanics each: E1-E4, E5, and E6-E7. Because the TNARNG had just transitioned to the MBT, there was a lack of experience on the engine. The test was designed by Dr. Malcolm Taylor, Chief Statistician, ARL, and the late Dr. Henry Tingey, University of Delaware. The field test was developed to test the preliminary analysis and no-start modules of the TED program.

Each mechanic inspected two engines, one with TED and one with the TMs. The engines had a random number of faults installed from a randomized list of possible faults. There was a one-hour time limit for each inspection. An observer, with a score card, was present with each mechanic to log faults and the times that each fault was located. The following test conditions approximated the mechanics' actual working environment:

- A DS maintenance bay and ground-hop support sets were available.
- TED or TMs were made available to the mechanics.
- Instructions to each mechanic were to inspect the engine and determine the faults. Observers provided no other assistance to the mechanics.
- An unrealistic, yet necessary condition, required mechanics to be situated so that they worked independently without any intercommunications.

There were three types of data collected during the field test: first, the observer's score card (mentioned previously), which served as the basis for the statistical analysis; second, a questionnaire completed by each mechanic, which allowed him to express his impressions of TED; third, each observer's recorded personal comments, which served as an additional source of information for further revisions.

Although the TNARNG soldiers had very little engine experience, the field test results show a definite trend. At each level, TED outperformed the current TM procedures (see Table 1). TED assisted the junior enlisted and the junior noncommissioned officers in finding at least twice as many faults as compared to the TMs. Note that even though TED is designed for junior mechanics, senior mechanics were able to increase their efficiency by using TED. Overall, the mechanics demonstrated a 96% increase in their ability to efficiently diagnose the engine (Taylor and Monyak 1994).

RANK	MANUAL FAULTS DETECTED	TED FAULTS DETECTED
E1 - E4	26%	52%
E5	11%	42%
E6 - E7	42%	56%
OVERALL	26%	51%

Table 1: Field Test Results

The ease of use became readily apparent to the observers during the initial training session. Because many of the mechanics had never used a computer, the observers allocated a one-hour training block for each mechanic. In less than 10 minutes, mechanics who had never used a computer were effectively maneuvering through the software and hardware. Soldier acceptance was also unanimously positive. Both computer- and noncomputer- literate mechanics readily accepted TED as the preferred tool for maintaining the engine.

5.0 Future Directions

The measure of TED's success is best gauged by its acceptance among the soldiers who will use it, the Abrams mechanics. While senior Army leaders have identified the cost benefits associated with TED, it is TED's utility that won acceptance by the soldier. As a result, the TED program has been targeted in several future directions.

The first obvious extension to the TED project involves the creation of a TED associate. Identified as a possible candidate to capitalize on TED's model of maintenance is the U.S. Army's Bradley Fighting Vehicle (BFV). Similar to the Abrams MBT, the BFV has its own special maintenance issues. Towards this end, the NGB has shown increasingly strong interest and continues its pursuit.

A second possible direction for consideration includes extending the TED project into the turret systems of the Abrams tank. Strong arguments have been made that ABOB technology would improve the efficiency and effectiveness of turret diagnostics. The final extension being weighed for TED future is research into the application of fuzzy logic and neural nets. Early results suggest that the incorporation of approximate reasoning methods would potentially allow better representation and integration of sensor data.

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